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OPTIMIZING THE ARMY'S AERIAL RECONNAISSANCE AND SURVEILLANCE ASSET MIX VIA THE JOINT PLATFORM ALLOCATION TOOL (JPAT)

by

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August 2013

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ABSTRACT

In an effort to preserve the Army's unmatched capabilities in aerial reconnaissance and surveillance (R&S), the Integrated Capabilities Development Team (ICDT) administered a large-scale study during fiscal years 2012 and 2013 to determine in which R&S platforms and sensors the Army should invest. This report describes the Joint Platform Allocation Tool (JPAT), a mixed integer linear program developed as part of this effort. JPAT determines an optimal R&S investment portfolio by evaluating cost, performance, and production timelines of existing and planned assets, as well as these assets' ability to perform against a 12-year prioritized mission demand signal. JPAT has informed critical resourcing decisions concerning the Army's long-term investment strategy.

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I. INTRODUCTION

A. BACKGROUND

The Army is currently transitioning from operations in Iraq and Afghanistan to preparation for new missions in 2020 and beyond. As Army operations often require significant materiel support, this transition requires the Army to consider how best to utilize the assets it employs in current operations, assets it is already committed to acquiring for the future, and assets—including those not yet in existence—that it may need for anticipated demands. An important asset class consists of aerial platforms and their associated sensors, which can provide valuable information on a variety of threats.

In September 2011, the Vice Chief of Staff, Army (VCSA) initiated a research effort aimed at helping the Army invest its limited resources most appropriately in the development, procurement, and fielding of aerial reconnaissance and surveillance (R&S) platforms. In response to the VCSA's directive, the Training and Doctrine Command (TRADOC) established the Aerial R&S Integrated Capabilities Development Team (ICDT). The ICDT undertook the task of determining an optimal investment strategy to shape the Army's R&S future capabilities with a near-term requirement of informing resource allocation decisions in the fiscal year 2015-2019 Program Objective Memorandum (POM).

In order to assist the ICDT in making a variety of strategic decisions, a team of analysts from the TRADOC Analysis Center (TRAC) and the Naval Postgraduate School (NPS) formulated and implemented a mixed-integer linear program called the Joint Platform Allocation Tool (JPAT). This report describes the JPAT model. JPAT evaluates the strategic implications of cost, sensor performance, mission requirements, and production timelines to produce an optimal procurement and assignment schedule of aerial R&S assets.

B. LITERATURE REVIEW

Optimization-based decision support tools have a rich history of application in military operations. A common element among many such decision support tools is the efficient use of limited resources, such as time, money, personnel, or materiel assets.

The Army's Program Executive Office (PEO) for Ground Combat Systems (GCS) developed an optimization model variably called the Campaign Plan Analysis Tool (CPAT) (Edwards, 2011) or the Capability Portfolio Analysis Tool (CPAT) (Ewing, Dell, MacCalman, and Whitney, 2013), to identify optimal Fleet investments given cost, schedule, and performance consideration (Edwards, 2011). The cost analysis supporting CPAT includes research, development, testing, and evaluation (RDTE) costs; average procurement unit costs (APUCs); and operations and maintenance (O&M) costs. The scheduling analysis considers modernization programs, desired program upgrades, and quantities, and the performance analysis assesses how well individual vehicles meet user-defined capability needs. CPAT's objective function maximizes Fleet performance based on weighted performance parameters and scheduled upgrades. JPAT also maximizes the performance of assets paired against prioritized mission demands.

The Department of Defense (DoD) Joint Air-to-Ground Missile (JAGM) study assessed various precision munitions purchasing options while considering cost, risk to the Force, and logistical burden (Eaton, Workman, & Smead, 2012). Like JPAT, JAGM is a mixed integer

linear problem and incorporates a large, complex set of input data that requires coordination among multiple data providers. JAGM employs munitions against mission demands (targets) to provide the greatest reduction in risk from unmet mission demands. In contrast to JPAT, JAGM uses Monte Carlo simulation on the model's solution to examine the impact caused by slight differences in munitions' probabilities of kill.

The TRAC Armored Multipurpose Vehicle (AMPV) portfolio model, developed in Excel, serves to reduce the number of possible mix alternatives from more than 40,000 to an analytically feasible set, as well as identify the best-performing course of action for further analysis within cost and manpower constraints (McIlrath, 2011). The model implementation leverages warfighter expertise to review the mission roles, identify the critical tasks and conditions across major combat operations (MCOs) and irregular warfare (IW) vignettes, and prioritize the AMPV attributes that mitigate or satisfy the tasks and conditions. Sensitivity analysis utilized different weighting ratios for MCOs and IW vignettes to determine if and where the solution changes. The selection coefficient development for the JPAT model required an extensive assessment for all configuration-to-mission, demand-to-intelligence requirement groupings, based on key characteristics of the mission demand and capabilities of the assets onboard the configuration.

A number of decision support tools facilitate personnel assignments. For example, Bausch, Brown, Hundley, Rapp, and Rosenthal (1991) designed the network optimization-based Manpower Assignment Recommendation System (MARS) to assign Marine Corps officers to billets during wartime mobilizations. MARS has significantly shortened the time required to plan a wartime mobilization while providing excellent officer-to-billet fits (Bausch et al., 1991). To assign Marine Corps officers to billets while simultaneously developing their professional skills and qualifications, Baumgarten (2000) developed an integer linear program known as the Officer Career Path Selection (OCPS) model. OCPS assigns officers to appropriate billets while also determining the number of officers assigned to various Military Occupational Specialties (MOSs) each year (Baumgarten, 2000). To assist with assigning enlisted Marines to billets, Tivnan (1998) developed the network-based Enlisted Assignment Model-Global (EAM-GLOBAL). Among other goals, EAM-GLOBAL seeks to balance staffing shortages while minimizing relocation costs (Tivnan, 1998). Personnel assignment models have also found application in the Army. For example, Dell, Ewing, and Tarantino (2008) developed an integer linear program called the Optimally Stationing Army Forces (OSAF) model to assign units to installations in a cost-effective way. OSAF has assisted the Army with analyses, including base realignment and closure (BRAC) decisions, since 2005 (Dell et al., 2008). Each of these models is similar to JPAT in that it seems to assign a limited resource (either personnel or aerial R&S assets) to a particular "target" (either billets or mission demands) in such a way as to maximize performance.

Optimization-based decision support tools also play a role in other decisions involving constrained resources. Brown, Goodman, and Wood (1990) describe the Combatant Primary Event Schedule (CPSKED), a generalized set partitioning model designed to assist in scheduling ships in the Atlantic. Similarly, Brown, Dell, and Farmer (1996) describe CutS, an integer linear program designed to optimize patrol and maintenance schedules of Coast Guard cutters. Like JPAT, these models demonstrate the ability of optimization to provide plans that address a number of objectives while satisfying a potentially complex set of constraints, and do so in a short amount of time relative to a manual planning process.

II. THE JOINT PLATFORM ALLOCATION TOOL (JPAT)

A. MODEL OVERVIEW AND TERMINOLOGY

JPAT's purpose is to determine the investment strategy and assignment of assets to mission demands that maximizes prioritized mission demand fulfillment. The ability of a particular asset to fulfill a particular mission demand is based on the *intelligence (INT) requirements* of the mission demand and the ability of the asset to satisfy these requirements. An INT requirement is simply a required sensing task; for example, full motion video, signal intelligence, or radar.

The assets considered by JPAT consist of *sensors*, each of which is capable of fulfilling one or more INT requirements, and *platforms*, each of which can carry a limited payload of sensors. In JPAT's terminology, a *system* is comprised of specified numbers of platforms and sensors. JPAT procures and distributes systems to *locations*. For modeling purposes, a location is a geographic entity with asset ownership and mission demand responsibility. The quantities of systems that are distributed are constrained by system production rate and limits on the total quantity of each system allowed to the field. JPAT can also retire a system when it is no longer useful or scheduled for mandatory retirement. Although an asset may face threats while in theater, JPAT does not consider attrition and survivability of equipment. Thus, retirement represents the only mechanism by which assets are removed from consideration. When retired, certain systems are replaced by other systems, in accordance with existing procurement commitments.

Once a system is distributed to a location, its component platforms and sensors can be combined with components of other systems to form various *configurations*. A configuration consists of one platform and one or more sensors; see Figures 1 and 2. JPAT assigns configurations to mission demands as appropriate, based on their sensing capabilities.
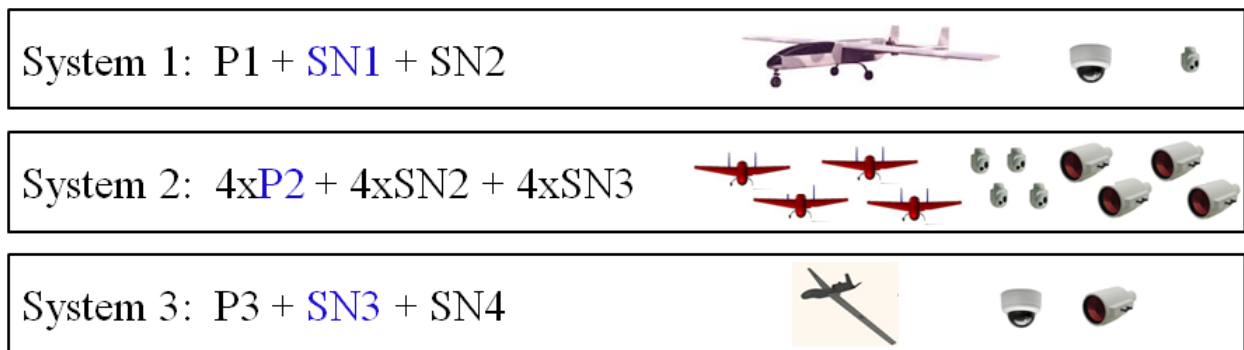

Figure 1.   Three example systems composed of platforms P1, P2, and P3, and sensors SN1, SN2, SN3, and SN4.

Configuration 1:
P2 + SN1 + SN3

Figure 2.   An example configuration consisting of equipment derived from multiple systems.

At times, it may be desirable to transfer equipment from one location to another. In keeping with operational reality, JPAT is constrained to transfer complete systems between locations, and transfers can only be triggered by high-priority missions. Both transportation of systems and assignment of configurations to mission demands are constrained by the time available: each type of equipment has a certain number of hours available per month, after adjusting for routine maintenance and other requirements. JPAT ensures that the total hours spent on transport and mission fulfillment do not exceed the total "pool" of hours available for each equipment type in each location.

It is important to note that although any feasible schedule of assignments must not exceed the hours available in this "pool," the reverse is not necessarily true. That is, it is possible to devise an assignment of configurations to mission demands that does not exceed the "pool" of available hours for any equipment type, but for which no feasible schedule exists. Thus, JPAT solves a relaxation of the classical scheduling problem. This relaxation allows JPAT to solve large-scale problems and produce an output that can be used as input for higher-resolution scheduling models.

Finally, JPAT models budgetary considerations. There are costs associated with distributing, maintaining, and retiring systems, and JPAT makes its distribution and retirement decisions while adhering to a maximum budget. In keeping with operational reality, money left unused at the end of a month can be used in the following month, unless the following month marks the beginning of a new fiscal year.

For computational efficiency, JPAT solves the problem iteratively using a rolling horizon approach. In each iteration r, JPAT considers the time horizon described by the set *TSET(r)*. The rolling horizon approach is described in more detail in Section II.C.

B.   MODEL FORMULATION

Indices and Sets [approximate cardinality]

$l, l' \in L$	Locations [7]
$m \in M$	Mission demands [~2,200]
$i \in I$	INT (intelligence) types [~15]
$r \in R$	Iterations in the rolling horizon model [user-defined]
$t, t' \in TIME$	Time steps [144]
$t \in T(r) \subseteq TIME$	Time steps in the considered in iteration r [user-defined]
$t \in N \subseteq TIME$	Time steps occurring at the beginning of a fiscal year [12]
$c \in C$	Configurations [~20]
$e \in E$	Equipment [40]
$y, y' \in Y$	Systems [13]

4

M(l)	Set of mission demands residing in location l
l(m)	Location of mission demand m (each mission demand resides in exactly one location)
$(y, y') \in REP$	Identifies the system y' replacing a retiring system y [~10]
$(t,y,l,l') \in GP$	Identifies systems y eligible to transfer from location l to location l' at time t [cardinality varies]

Input Data [units]

$iq_{e,l}$	Initial quantity of equipment e in location l at time 0 [number of items]
$d_{t,m}$	Number of times mission demand m is present at time t [number of occurrences]
$ok_{m,i,c}$	Number between 0 and 1 indicating the ability of configuration c to fulfill INT type i in mission demand m [unitless]
omc_e	Operation and maintenance (O&M) cost per month for equipment e [\$M]
pc_y	Procurement cost for system y [\$M]
rc_y	Retirement cost for system y [\$M]
$b_{t,y}$	Maximum budget for system y at time t [\$M]
$pr_{t,y}$	Maximum production rate of system y at time t [number of items]
p_m	Number between 0 and 1 indicating the importance of mission demand m [unitless]
$ec_{c,e}$	Number of equipment e in configuration c [number of items]
$es_{y,e}$	Number of equipment e in system y [number of items]
he_e	Hours available for transport and missions per time period for equipment e Accounts for regular maintenance hours, etc. [hours]
hm_m	Hours required to perform mission demand m, not including equipment-specific setup and takedown time [hours]
$hi_{m,i}$	Hours required for INT type i in mission demand m [hours]
su_e	Time to set up, take down, and maintain equipment e per assignment [hours]
$transdays_{y,l,l'}$	Time required to transfer system y from location l to location l'. Includes actual transit time as well as packing, unpacking, etc. [days]
$sr_{m,c}$	Sorties required in order for configuration c to fully complete mission demand m [number of sorties]
$upperbounds_y$	Maximum number of system y that can ever be distributed, total across all time [number of items]
$mr_{t,y}$	Total number of system y that must be retired by time t [number of items]
$intial_y$	Number of system y initially in theater [number of items]

Calculated Data

$max_{t,y}$	Maximum total number of system y that can have been distributed as of time t [number of items]

$$max_{t,y} = \min(upperbounds_y - initial_y, \sum_{t'=1}^{t} mpr_{t',y})$$

$ht_{e,y,l,l'}$	Hours to decrement from equipment type e when transporting system y from location l to location l'. Assumes that any transfers that require more than 1 month (26 operational days) are completed in 1 month [hours]

$$ht_{e,y,l,l'} = \min[1, \frac{transdays_{y,l,l'}}{26}]he_e es_{y,e}$$

Positive Integer Variables

$G_{t,y,l,l'}$	Number of system y transferring from location l to location l' at time t
$Z_{t,y,l}$	Number of system y retiring from location l at time t
$D_{t,yl}$	Number of system y distributed to location l at time t

Binary Variables

$P_{t,c,l} = 1$ if sufficient equipment is present to create configuration c at time t in location l; 0 otherwise

Positive Variables

$X_{t,m,c,i}$	Number of hours configuration c is assigned to INT type i for mission demand m at time t
$S_{t,m,c}$	Number of sorties flown by configuration c against mission demand m at time t
$Q_{t,e,l}$	Quantity of equipment e present in location l at time t
B_t	Budget rolled over from previous time period at time t

Formulation

For improved readability, JPAT's formulation is shown in Figure 3.

The objective function (1) maximizes the weighted mission demand coverage, weighted by mission demand priority and configuration performance. Constraint set (2) ensures that intelligence requirements are not oversatisfied by the assigned configurations. Constraint sets (3-4) maintain a record of the quantity of each equipment type available in each location, beginning with the initial quantity (4) and updating the quantity based on system procurements, retirements, and transfers in subsequent time steps (3).

Constraint sets (5-8) ensure that configurations are employed appropriately based on equipment availability. Constraint set (5) forces $P_{t,c,l}$ to take on a value of zero if any piece of equipment require to construct configuration c is not present in a sufficient quantity in location l at time t; otherwise, $P_{t,c,l}$ is allowed to take on a value of one. Constraint set (6) uses the variables $P_{t,c,l}$ to control the number of sorties flown by configuration c: if $P_{t,c,l} = 0$, then configuration c cannot fly any sorties against any mission demands in location l at time t. Otherwise, configuration c can fly any number of sorties so long as it does not exceed the number of sorties required to completely satisfy the mission demand. Constraint set (7) ensures that the time spent covering intelligence requirements is appropriate given the number of sorties flown. Finally, constraint set (8) ensures that the hours spent fulfilling mission demands and transferring from one location to another do not exceed the "pool" of hours available for each equipment type.

Constraint sets (9-11) ensure that budgetary limitations are observed. Constraint set (9) calculates the monthly budget rollover B_t while accounting for equipment maintenance, system procurement, and system retirement costs. Because B_t is a nonnegative variable, constraint set (9) ensures that the available budget is not exceeded on months that do not mark the beginning of

a fiscal year. Likewise, constraint set (10) performs this function for months that do mark the beginning of a fiscal year, while constraint set (11) sets B_t to zero for months at the beginning of a fiscal year.

Constraint sets (12-13) control distribution and retirement of systems. Constraint set (12) ensures that the total number of system y distributed as of time t does not exceed the limits posed by system production rates and fielding restrictions. Constraint set (13) ensures that any system y' that "upgrades" a system y is not distributed until its predecessor y is retired.

Finally, constraint sets (14-21) declare variable types.

$$\max_{\substack{P,\,G,\,Z \\ D,\,S,\,X, \\ B,\,Q,}} \quad z = \sum_{(t,m,c,i):t\in T(r),d_{t,m}>0,hi_{m,i}>0} pm\,ok_{m,i,c}\frac{X_{t,m,c,i}}{\sum_{i'} hi_{m,i'}} \tag{1}$$

$$\text{s.t.} \quad \sum_{c:ok_{m,i,c}>0} X_{t,m,c,i} \le hi_{m,i}d_{t,m} \qquad \forall\ t\in T(r),m,i:d_{t,m}>0,hi_{m,i}>0 \tag{2}$$

$$Q_{t,e,l} = Q_{t-1,e,l} + es_{y,e}\sum_y (D_{t,y,l} - Z_{t,y,l} + \sum_{l'}(G_{t,y,l',l} - G_{t,y,l,l'})) \qquad \forall\ t\in T(r),e,l:t>1 \tag{3}$$

$$Q_{t=1,e,l} = iq_{e,l} \qquad \forall\ e,l \tag{4}$$

$$P_{t,c,l} \le \frac{Q_{t,e,l}}{ec_{c,e}} \qquad \forall\ t\in T(r),l,c,e:ec_{c,e}>0,\exists m\in M(l):d_{t,m}>0 \tag{5}$$

$$S_{t,m,c} \le sr_{m,c}d_{t,m}P_{t,c,l(m)} \qquad \forall\ t\in T(r),m,c \tag{6}$$

$$X_{t,m,c,i} \le \frac{hm_m S_{t,m,c}}{sr_{m,c}} \qquad \forall t\in T(r),m,c,i:ok_{m,i,c}>0,hm_{m,i}>0,d_{t,m}>0 \tag{7}$$

$$\sum_{y,l'} ht_{e,y,l,l'}G_{t,y,l,l'} + \sum_{c,m\in M(l)} ec_{c,e}\left(\frac{hm_m}{sr_{m,c}}+su_e\right)S_{t,m,c} \le he_e Q_{t,e,l} \qquad \forall\ t,e,l \tag{8}$$

$$B_t = B_{t-1} + \sum_y b_{t,y} - \sum_{y,l}(pc_y D_{t,y,l} + rc_y Z_{t,y,l}) - \sum_{e,l} omc_e Q_{t,e,l} \qquad \forall\ t\in T(r)\setminus N:t>1 \tag{9}$$

$$\sum_{y,l} pc_y D_{t,y,l} + \sum_{y,l} rc_y Z_{t,y,l} + \sum_{e,l} omc_e Q_{t,e,l} \le \sum_y b_{t,y} \qquad \forall\ t\in T(r)\cap N \tag{10}$$

$$B_t = 0 \qquad \forall\ t\in T(r)\cap N \tag{11}$$

$$\sum_{l,t'\le t} D_{t',y,l} \le max_{t,y} \qquad \forall\ t\in T(r),y \tag{12}$$

$$\sum_{t'\le t,y:(y,y')\in REP} Z_{t',y,l} \ge \sum_{t'\le t} D_{t',y',l} \qquad \forall\ t\in T(r),l,y':\exists y:(y,y')\in REP \tag{13}$$

$$P_{t,c,l} \in \{0,1\} \qquad \forall\ t\in T(r),c,l \tag{14}$$

$$G_{t,y,l,l'} \in \mathbb{Z}^+ \qquad \forall\ (t,y,l,l')\in GP:t\in T(r) \tag{15}$$

$$Z_{t,y,l} \in \mathbb{Z}^+ \qquad \forall\ t\in T(r),y,l \tag{16}$$

$$D_{t,y,l} \in \mathbb{Z}^+ \qquad \forall\ t\in T(r),y,l \tag{17}$$

$$X_{t,m,c,i} \ge 0 \qquad \forall\ t\in T(r),m,c,i \tag{18}$$

$$S_{t,m,c} \ge 0 \qquad \forall\ t\in T(r),m,c \tag{19}$$

$$Q_{t,e,l} \ge 0 \qquad \forall\ t\in T(r),e,l \tag{20}$$

$$B_t \ge 0 \qquad \forall\ t\in T(r) \tag{21}$$

Figure 3.   JPAT's mathematical formulation.

C. ROLLING HORIZON APPROACH

To reduce the computational burden of running JPAT, the study team implemented a rolling horizon approach. Two user-selected parameters govern the behavior of the rolling horizon approach: H, the number of time steps over which the model considers the future (sometimes called the "lookahead"), and h, the number of time steps over which the variables are fixed in each iteration ($h<H$). In iteration r, the model solves over a window of time steps ranging from the beginning time $b(r) = (r-1)h +1$ to the final time $b(r)+H-1$. After solving, the model fixes values from $b(r)$ to $b(r)+h-1$, shifts the window forward h steps so that $b(r+1) = b(r)+h$, and repeats the process. Thus, the set $TSET(r)$ is obtained as follows:

$$TSET(r) = \{t \in T | (r-1)h + 1 \le t \le (r-1)h + H\}).$$

JPAT covers a total time span of 12 years, which is divided into one-month time steps. Once the solver window reaches the final time step ($t = 144$), no additional benefit is gained from fixing variables over a reduced window. Thus, the model performs a total of $\left\lceil \left(\frac{144-H}{h}\right) + 1 \right\rceil$ iterations. Table 1 illustrates the rolling horizon approach for $H=60$, $h=12$.

Iteration, r	Beginning of Solver Window, $b(r)$	End of Solver Window	Time Steps Over Which Variables are Fixed
1	1	60	1-12
2	13	72	13-24
3	25	84	25-36
4	37	96	37-48
5	49	108	49-60
6	61	120	61-72
7	73	132	73-84
8	85	144	85-144

Table 1.   Iterations performed in the rolling horizon approach for $H=60$, $h=12$.

D. INPUT DATA

An extensive team of Army analysts and subject matter experts contributed to JPAT's input data (see Table 2). While most of the assumptions underlying JPAT's input data are straightforward, we now describe a few key assumptions that are essential in understanding JPAT's functionality.

As described, time is a key constraint governing which mission demands can and cannot be satisfied with the equipment available. It is important to note that the hours required for missions, hm_m and $hi_{m,i}$, only account for dwell time, not transit time. Future work may incorporate transit time. The time required to transfer a system, $transdays_{y,l,l'}$, includes preparation, travel, and unit stand-up time. The set-up time, su_e, accounts for all aspects of the management of assets on the ground prior to take-off. Sortie duration requirements consider endurance thresholds from launching to landing to establish the number of employments required, $sr_{m,c}$; note that the model can assign a fractional employment if necessary.

Input Data	Source(s)
Initial inventories ($initial_y$, $iq_{e,l}$)	Intelligence and Security Command (INSCOM)
System upper bounds ($upperbounds_y$, $mr_{t,y}$)	
System transfer times ($transdays_{y,l,l'}$)	
MD/INTEL durations (hm_m, $hi_{m,i}$)	Subject Matter Experts (SMEs) from the Centers of Excellence
MD priorities (p_m)	
MD locations ($l(m)$, $M(l)$)	
MD frequencies ($d_{t,m}$)	
Budget data ($b_{t,y}$)	Army Resource Management Office (G-8)
Production rates ($pr_{t,y}$)	Program Managers (PMs) for the aerial R&S systems
Cost data (pc_y, rc_y, omc_e)	
Equipment hours available (he_e)	
Equipment setup time (su_e)	
System configurations ($es_{y,e}$)	
Configuration data ($ok_{m,i,c}$, $ec_{c,e}$, $sr_{m,c}$)	Army Materiel Systems Analysis Activity (AMSAA)

Table 2. Input data and providers.

Performance coefficients, $ok_{m,i,c}$, are designed to account for variations in terrain and weather conditions. Production rates, $pr_{t,y}$, account for equipment manufacture, unit stand-up, and deployment to the field. Equipment maintenance costs, omc_e, only include standard required maintenance and do not depend on usage.

1. Data Preprocessing

The initial dataset provided to the study team was extremely large and resulted in high memory usage and computation time, even when used in conjunction with a rolling horizon approach. Fortunately, careful preprocessing resulted in a significant reduction in both the volume of data and the computational resources required to run the model.

The first preprocessor aggregates mission demands with identical attributes ($l(m)$, $ok_{m,i,c}$, p_m, hm_m, $hi_{m,i}$, and $sr_{m,c}$). This preprocessor improved runtime and decreased the number of distinct mission demands from approximately 2,200 to approximately 250.

The second preprocessor uses information about the performance of the possible configurations-mission demand pairs ($ok_{m,i,c}$), combined with the composition of the configurations ($ec_{c,e}$), to eliminate configuration-mission demand assignments that are provably unnecessary in an optimal solution. For example, consider two configurations, *c1* and *c2*, and assume that the equipment used in *c1* is a strict subset of that used in *c2*. That is, every piece of equipment used in *c1* is also used in *c2*, but not every piece of equipment used in *c2* is also used in *c1*. Furthermore, assume that *c1* performs at least as well as *c2* for mission demand *m1*. That

is, $ok_{m1,i,c1} \geq ok_{m1,i,c2}$ for all i. Suppose that $c2$ is assigned to $m1$ in a feasible solution. Then, it is possible to construct another solution by replacing any assignment of $c2$ to $m1$ with an assignment of $c1$ to $m1$. Such a solution would definitely be feasible, since all of the equipment needed to assemble $c1$ was present and had sufficient hours available in the solution involving $c2$. Moreover, the objective value would improve or remain unchanged, since $ok_{m1,i,c1} \geq ok_{m1,i,c2}$. Therefore, it is possible to remove from consideration the possibility of assigning $c2$ to $m1$ by setting $ok_{m1,i,c2} = 0$ for all i. A preprocessor that performs such simplifications reduced the number of (c, m) pairs considered by approximately 80% and dramatically improved computation time.

III. SUMMARY AND FUTURE WORK

A. SUMMARY AND MODEL IMPACT

An optimization approach to a large-scale problem, such as the aerial R&S study, is generally not expected to provide a highly detailed, final answer. Rather, it is intended to provide a "rough cut" at the solution and generate output that can enable higher resolution models to obtain greater insights. JPAT is the beginning of the answer to the complex and critical problem of what assets will meet the Army's current and future aerial R&S needs. In essence, JPAT's output provides an assignment of assets to mission demands. By tracking the time spent covering each intelligence requirement, JPAT can determine which mission demands were fully satisfied, and within those mission demands not fully satisfied, which INT requirements remained uncovered. In turn, further postprocessing can determine the residual operational risk resulting from unsatisfied requirements. These insights, gained through careful sensitivity analysis and interpretation of results, are instrumental in guiding the Army's procurement decisions. Although the results of JPAT are classified, we note that the configuration-to-mission demand assignments produced by JPAT have undergone additional analysis of processing, exploitation, and dissemination (PED) and have been briefed to Army leadership. The JPAT model has also undergone a peer review by two different boards—a group of analysts at the Institute for Defense Analyses (IDA) and a group of faculty from the Naval Postgraduate School—prior to full-scale implementation.

B. FUTURE WORK

1. Effectiveness Model

In its initial implementation, JPAT provides results in monthly time steps over a 12-year time frame. Modifications to JPAT and its data, however, yield a higher-resolution model known as JPAT-Effectiveness (JPAT-E) that provides results at daily time intervals. JPAT-E takes the inventory quantities from an initial JPAT run and determines how well the inventory in a particular location can cover the demand signal in that location over the abbreviated time frame (for example, two weeks). Like JPAT, JPAT-E assigns assets while observing a "bin of hours" time constraint rather than creating a full schedule. The impact of this relaxation, however, is mitigated by the shorter duration of JPAT-E's time steps.

2. Expanded Applications

Plans exist to extend JPAT's capabilities to consider mission demands that are not limited to R&S, such as communication support missions. Additionally, the pool of assets considered by JPAT will expand to include assets other than those with a program of record, or those that are quick reaction capabilities or in developmental stages.

Preliminary exploration of the modifications necessary to incorporate these additional capabilities has already begun. The primary modeling challenge arises from the fact that once the new assets are included in the model, various factors prevent certain pieces of equipment from being operated simultaneously. For instance, each piece of equipment draws a certain amount of power, and the platform may be unable to power all equipment simultaneously. Other

physical limitations relate to interference between pieces of equipment; for example, it would be unwise to operate jammers and radios simultaneously. One way to accommodate these limitations is to enumerate groups of equipment that may be operated simultaneously and to designate these groups using an index, g. Then, a modified version of JPAT capturing these physical limitations would include the following modifications in addition to the existing formulation described in Section II.B:

Indices and Sets

$g \in GR$ Maximal groups of equipment that may be operated simultaneously

$(i,g) \in SAT$ Identifies groups g containing equipment that satisfies INT type i

Positive Variables

$O_{t,m,c,g}$ Number of hours group g is operated in configuration c in support of mission demand m at time t

Formulation

$$X_{t,m,c,i} \leq \sum_{g:(i,g) \in SAT} O_{t,m,c,g} \qquad\qquad \forall\, t,m,c,i \quad (22)$$

$$\sum_g O_{t,m,c,g} \leq \frac{hm_m}{sr_{m,c}} S_{t,m,c} \qquad\qquad \forall\, t,m,c \quad (23)$$

$$O_{t,m,c,g} \geq 0 \qquad\qquad \forall\, t,m,c,g \quad (24)$$

Constraint set (22) ensures that the number of coverage hours recorded for INT type i does not exceed the total number of hours that a piece of equipment capable of covering INT type i was operated for each configuration c, mission demand m, and time step t. Constraint set (23) ensures that the total time spent operating groups does not exceed the total hours flown by each configuration c supporting mission demand m at time t. Finally, constraint set (24) defines the variable type for variable $O_{t,m,c,g}$.

Note that the tractability of this modified formulation depends on the efficiency with which the members of GR can be enumerated. For preliminary modeling purposes, we assume that the physical limitations dictating membership in GR can be captured via a set of knapsack constraints:

$$\sum_e r_{e,d} U_e \leq m_d \qquad\qquad \forall\, d\,.$$

Here, the index e reflects pieces of equipment (as before), the index d reflects knapsack dimensions (e.g., power), the parameter $r_{e,d}$ reflects equipment e's resource consumption along dimension d (e.g., power consumed), the binary variable U_e reflects membership of equipment e in group g, and the parameter m_d reflects the resource availability along dimension d (e.g., power available on the platform). Any binary vector U satisfying these constraints represents a subset of equipment that can be turned on simultaneously, i.e., an element of GR. Then, one can iteratively solve the following feasibility problem to generate a new member of GR, given a set of existing members:

Indices and Sets

$e \in E$	Equipment types
$d \in D$	Knapsack dimensions
$i \in I$	Iterations

Parameters

$r_{e,d}$	Resource consumption of equipment e along dimension d
m_d	Resource availability along dimension d
$\underline{u}_{e,i}$	Indicates usage of equipment e in group generated in iteration i

Binary Variables

$U_e = 1$ if equipment e is selected for inclusion in the maximal group being generated; 0 otherwise
$Y_{e,d} = 1$ if inclusion of equipment e would violate the knapsack constraint along dimension d;
0 otherwise

Formulation

$$\max_{U,Y} \quad 0$$

$$\text{s.t.} \quad \sum_e r_{e,d} U_e \le m_d \qquad\qquad \forall\, d \qquad (25)$$

$$U_e + \sum_d Y_{e,d} \ge 1 \qquad\qquad \forall\, e \qquad (26)$$

$$Y_{e,d} \le 1 + \frac{\sum_{e'} r_{e',d} U_{e'} + r_{e,d}\left(1 - U_e\right) - m_d}{\sum_{e'} r_{e',d}} \qquad\qquad \forall\, e,d \qquad (27)$$

$$\sum_{e:\underline{u}_{e,i}=0} U_e + \sum_{e:\underline{u}_{e,i}=1}\left(1 - U_e\right) \ge 1 \qquad\qquad \forall\, i \qquad (28)$$

$$U_e, Y_{e,d} \in \{0,1\} \qquad\qquad \forall\, e,d \qquad (29)$$

Constraint set (25) captures the physical constraints governing simultaneous equipment usages. Constraint set (26) ensures that the group generated is maximal; in particular, it ensures that each piece of equipment e is either selected for inclusion, or its selection would cause at least one knapsack constraint to be violated. Constraint set (27) ensures that the variables denoting violation of knapsack constraints are set correctly. Here, it is important to assume that $m_d \le \sum_{e'} r_{e',d}$; if this is not the case, we can set $m_d = \sum_{e'} r_{e',d}$ without impacting the feasible solutions to the knapsack problem. Constraint set (28) ensures that the group generated differs from all previous groups that have been generated. Constraint set (29) declares variable types.

Preliminary experimentation indicates that this formulation can be used to generate maximal groups of equipment within an acceptable amount of time. It is important to note that the inclusion of only *maximal* groups in the modified JPAT model reflects an implicit

assumption that there are no restrictions on *total* resources consumption, only *instantaneous* resource consumption. While this assumption has been supported by subject matter experts, the authors recommend verifying it again should the model described in this section ever be used operationally.

3.   Utility Assessment

The objective function of JPAT maximizes mission demand coverage with respect to mission demand priority, mission demand to configuration performance, and time spent covering each intelligence requirement of a mission demand. In the earliest versions of JPAT, these three factors contributed equally to the objective function value. The larger study team, however, has recently recognized the need for high-priority missions to be met above all else. Modifications to JPAT's formulation to address this need are currently underway.

4.   Transfer Minimization

A key capability in the JPAT model is the ability to transfer assets between locations to meet high-priority mission demands. There is currently no penalty in the objective function for transfers because Army leadership deemed that fulfillment of mission demands should take precedence. The lack of a penalty for transfers, however, means that unnecessary transfers sometimes occur. Work is underway to eliminate these "spurious transfers," while maintaining a high objective value.

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